Characterization Testing- A Predictive Maintenance Advantage

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Abstract: Knowing that a traditional time-directed preventive maintenance program is limited in its flexibility and effectiveness, the CHAR 921 characterization system software was developed as an open architecture design. This enables linking to additional data base modules and integrating predictive maintenance data collection and data analysis into a single system. Applications for which the Characterization System is most effective:

- Distributed Control Systems (DCS)
- Fire Protection/Security Systems
- Pressure Transmitters
- Power and Instrumentation Cables
- Relay Coils
- Motors
- EMI (Noise Problems)
- RTDs
- Solenoids
- UPS Inverters/Chargers
- Flow Transmitters
- Thermocouples

By taking advantage of the synergistic benefits realized when the results of several techniques are brought together, power plant management has a powerful tool which directs the focus of maintenance activities to "real time" equipment condition needs and not simply performing maintenance as a function of time.

Keywords: Characterization system, predictive maintenance, condition monitoring, time domain reflectometry, transmission line, circuit modeling, lumped element impedance, distributed element impedance.

Introduction: A characterization system is a combination of electronic measurement instruments and database management under computer control. The hardware provides the means to accurately measure those electrical parameters that have already been defined through standards and manufacturer's specifications: resistance, capacitance, inductance, and time domain reflectometry signature. The software provides the ability to manage the electrical test data. The software has two equally important roles: first, the acquisition of the data so that it is truly representative of the accuracy of the test equipment; and second, the storage, retrieval and processing of the data so that it can contribute to improved equipment operation. The electrical variables being characterized were always known to be important. In the past, to make life easier for the end user, a manufacturer would pick the most critical and most easily measured variable(s) for monitoring. For example,

winding resistance might be the critical parameter for a motor to be checked periodically. Additional tests to measure capacitance or inductance might only be specified for troubleshooting.

Circuit Characterization: Characterizing a circuit is based on the concept that operational circuits contain both lumped and distributed impedance elements. Basic courses in alternating current (AC) theory treat the various circuit parameters as discrete or "lumped" quantities. The passive circuit elements include resistance (R) measured in ohms, inductance (L) in henrys and capacitance (C) in farads. For the lumped elements it is assumed that they have negligible physical size and are essentially pure.

1. Resistor - neglect the wire wound inductance.

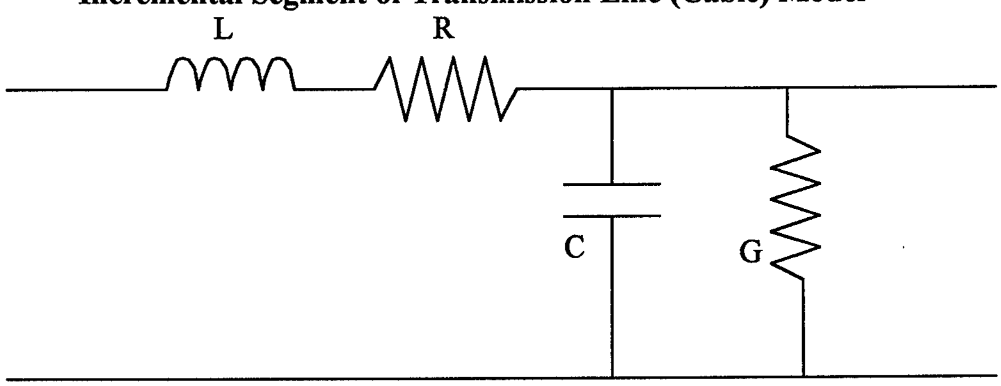
2. Inductor - neglect wire resistance and wire to wire capacitance

3. Capacitor - neglect lead wire resistance

The concept of negligible physical size simply means that distance between leads is insignificant. Distributed element impedance brings size into consideration such that you can't ignore the distance between leads or the time required for current to travel through a relay coil or motor winding. A cable is the best example of distributed element impedance. The Characterization System uses conventional test equipment for measurements of the lumped element impedance and Time Domain Reflectometry for measuring the distributed element impedance of a circuit.

Characterization Data : Analysis of characterization data is based on the understanding that nearly all power and control circuits can be treated as two port networks and analyzed as radio-frequency (RF) transmission lines with a load at the end of the line. This allows circuit components to be separated in time and analyzed individually even while testing from a remote location.

Incremental Segment of Transmission Line (Cable) Model



L = Inductance
R = Resistance
C = Shunt Capacitance
G = Shunt Conductance

In the model above, R is the series resistance of the line, it includes both conductors. It varies with frequency because of skin effect. It may be negligible or quite large, typically it is between these extremes. Note that the dimensions of R must be ohms/unit length, that is ohms/meter, ohms/feet.

The series inductance, L, occurs because the magnetic flux surrounding each incremental length of line links with the adjacent incremental lengths of conductor on either side. The effects of the series L may also be large or small, depending on line frequency, and application. The units of series inductance are henrys/unit length.

The shunt conductance, G, causes leakage currents which dissipate power. It is caused by less-than-infinite insulation resistance. For a well-insulated overhead electric power transmission line, G is nearly zero. This is not true for most other transmission lines, however. The units for shunt conductance are reciprocal resistance per unit length, that is mhos/unit length or siemens /unit length.

The shunt capacitance, C, is due to the physical proximity of two or more conductors separated by a dielectric. It causes displacement currents which dissipate no power but may be troublesome for other reasons. These may be negligible for a short, overhead, power line, and immense for a buried high-voltage cable. The units for shunt capacitance are farads/unit length.

We will examine each of these parameters and note the contribution that changes in each makes to the probability of circuit failure.

Wire series resistance (R) is determined prior to manufacture of the wire by choice of conductor size, physical configuration (for example, stranded or solid) and material. The choice of each is made with regard to allowable current density, amperes/unit area of conductor, for an acceptable heat rise in the expected operating environment. The required mechanical properties (tensile strength and flexibility, for example) are also factors in conductor design. The only change in series resistance that we may expect under normal operating conditions, after the conductor is placed in service, is the change due to variations in temperature. The resistance change with temperature is a well-understood phenomena, and is given by: $Rt_2 = Rt_1 [1 + \propto (t_2 - t_1)]$

Rt_2 = Resistance at temperature t_2, ohms
Rt_1 = Resistance at temperature t_1, ohms
t_1 = Present temperature, degrees Celsius
t_2 = Reference temperature, degrees Celsius
$\propto$ = Temperature coefficient of resistance
= 0.0039 for copper, 0.001146 for aluminum, per degree Celsius.

Using the above, we may investigate changes with temperature. A circuit consisting of 1000 feet of solid copper 12-gauge wire has a resistance of 1.652 ohm at a temperature of 59^0F (15^0C), for example. At 131^0F (55^0C) its' temperature increases to only 1.91 ohms,

an increase of 15.6%. Changes of this magnitude are easily managed, their effects are minimized by careful system design. Major resistance changes from other causes are most unlikely. Remember that resistance is: $R = \frac{\rho l}{A}$ ohms

ρ = Resistivity, ohm-meters
l = conductor length, meters
A = Conductor cross-section area, meters

The resistivity is a property of the conductor material, it is fixed at manufacture, and thereafter can vary only with temperature. A non temperature-related gross change in resistance then requires a gross change in either conductor length or cross-sectional area, or both. Such could conceivably be caused by severe mechanical damage, or severe corrosion which reduces the conductor cross-sectional area by a significant amount over a considerable length. Termination or splice problems are a far more likely source of series resistance changes, however. Each requires a breach in the protective insulation which is a possible entry point for moisture or other contamination. Two other possibilities must also be noted.

1. A less-than-perfect connection can lead to heating, loosening, and eventual arcing and failure.

2. If vibration is present, care must be taken at installation to properly distribute the bending of the conductor. Failure to do so will lead to metal crystallization and eventual failure.

We may summarize all of the above in a few words. Resistance changes in the line are highly unlikely in the absence of gross mechanical or chemical damage. Resistance changes in splices or terminations are quite possible, however.

Line series inductance (L) is due to the flux surrounding an incremental length of line linking with the immediately adjacent lengths on either side. The amount of flux for a given current is strongly affected by the permeability of the medium surrounding the conductor. Remember that the permeability of iron and iron alloys is high, about 2000 times the permeability of air. Air and most other materials have a very low permeability, they are magnetically transparent. We may immediately recognize that series inductance will be affected if we insert a twisted-pair line in a steel pipe, for example. The effect may be less than we expect, however, for the flux is largely confined to the space between the conductors. Once installed, changes in series inductance are highly unlikely. It is difficult to envision a situation in which a ferromagnetic material is placed in, or removed from, the space between the conductors, so we may remove such changes from our subjects for consideration.

Line shunt capacitance (C) in a uniform, undamaged, uncontaminated line is a function of conductor size and spacing, and of the dielectric properties of the material surrounding the conductors. The conductor insulation is usually the only material of interest. The manu-

facturer selects an insulation with due regard to many factors. Its' mechanical properties include physical strength, flexibility, and ease of application at manufacture. Voltage withstand capability is important, as is expected service life. The insulation will be assaulted by heat, radiation, chemicals, and voltage stress. It must withstand all expected hazards without significant loss of mechanical or electrical capabilities. For most applications, the dielectric constant, or relative permittivity, is low, or absent from, the list of factors in choosing an insulation. Changes in this will be of major interest in the use of Characterization test data. Changes in dielectric constant causes changes in line capacitance. They are usually clear indicators of present or incipient circuit problems. They are highly likely and are easily detected and localized with Characterization system testing. Basic physics describes the parallel-plate capacitor whose capacitance is given by:

$C = \underline{\varepsilon A}$ Farads

ε = permittivity of material between plates, Farads/meter

A = area of each plate, meters

1 = distance between plates, meters

The permittivity is usually given as:

$\varepsilon = \varepsilon o \varepsilon r$

εo = permittivity of a vacuum

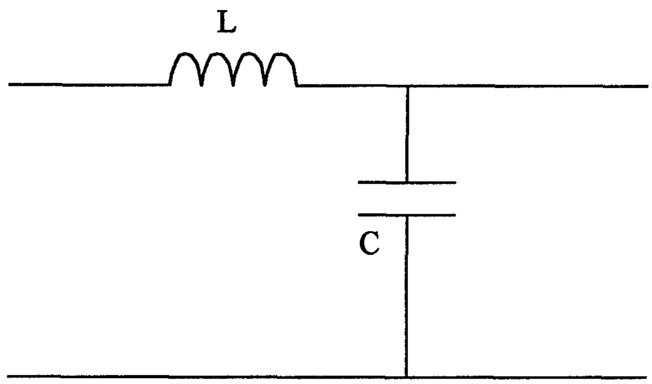
εr = relative permittivity of dielectric used

$$= \frac{10^{-9} \text{ Farads}}{36 \quad \text{meter}}$$

Relative permittivity varies widely. A vacuum has a relative permittivity of 1.0000 by definition. Values for some other common materials are shown below.

Distilled Water	Relative Permittivity
Air	1.0006
Polystyrene	2.7
Rubber	3.0
Bakelite	5.0
Flint Glass	10.0
Distilled Water	81.0

Simplifying the cable model shown earlier, to a lossless line model allows us to easily define changes in the characterization data of individual circuits by simply evaluating the lumped element impedance for change and then correlating the change to a location in the circuit by evaluating the distributed element impedance which is a function of time (as seen by the TDR). Since most transmission lines are nearly losses, we will only consider the reactive components L & C in a simplified model of our incremental line below:



L = Inductance
C = Capacitance

If we could immerse this two-wire line in water, we would see the shunt capacitance measurement increase by a factor of $\approx$ 80. Since the characteristic impedance for the lossless line is: $Z_c = \sqrt{Z/C}$ ohms; a change of 80 in the value of C leads to:

$Z_c = \sqrt{Z/80C} = \sqrt{1/80} \times \sqrt{L/C} = 0.111 \times \sqrt{L/C}$ ohms. So if the characteristic impedance of our model was 200 ohms, it now reduces 22.2 ohms as a function of moisture intrusion of the dielectric. This is not an uncommon occurrence in a power plant or industrial facility. For most instrumentation and control circuits, this change in characteristic impedance, is in itself of little consequence; the circuit will usually operate normally. The intrusion of moisture into the conductor insulation isn't necessarily harmful in itself, however the long-term prognosis is usually failure.

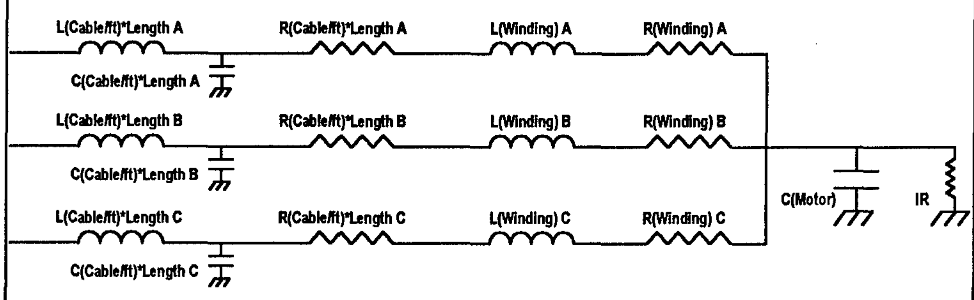
Understanding the electrical parameters being characterized and factors which can affect these test parameters allows comparative analysis to be automatically performed by the characterization system. Analysis reports are generated automatically using predefined tolerances for the various circuits being tested. Afterall, the idea of predictive maintenance is to establish a program for the equipment of concern which allows comparative analysis of test data in advance of actual failure. Of course, the goal is to do this in the same amount of time, or less, than was originally allocated to perform any testing being done as part of an existing Maintenance Program.

Case Study: The following case study describes characterization testing of motors for predictive maintenance. This summary will focus on comparison of the most critical electrical parameters being trended and provides insight on how the determination of electrical condition of each motor are prioritized for maintenance.

Background: The analysis of the motors begins by modeling each of them as shown in Figure 1. The model consists of the resistance, capacitance, and the inductance of both the cables and the motor. Stresses that cause electrical failure include differential thermal stresses, different coefficients of expansion, varnish weakening at high temperatures, magnetic force due to winding currents, environmental contaminants and moisture. These

stresses cause looseness, motion, and wear of the insulation. Each of the materials used to fabricate motor insulation systems has different sensitivities to these stresses. A Characterization System test on a motor, made from the motor control center or switchgear, will determine the quality of the cable and motor insulation, condition of the motor connections, and will provide impedance data which can be flagged at predetermined values for changes in capacitance, inductance, dissipation factor etc. Determination can be made regarding problems with the motor or cable without having to disconnect the motor from the cable. When trended this data can provide a meaningful and accurate assessment of the stator winding insulation system.

Figure 1: Reactor Coolant Pump Motor Analysis Model



The critical test measurements automatically acquired, analyzed and trended with the Characterization System are described below:

1. loop resistance
2. loop impedance
3. insulation resistance / polarization ratio
4. capacitance/dissipation factor
5. time domain reflectometer signature

Details of two critical factors used in analyzing motors are: <u>Dissipation Factor</u>**:** The dissipation factor is a **key electrical indicator** for predicting failures with motors. Purely conductive losses between conductors are small in a well insulated line. There is however, also a "dielectric hysteresis" loss which must be included in the shunt conductance . It will be recalled that the line capacitance stores energy of : 1/2 CV^2 joules-second. When energized by the AC line, capacitance stores energy for 1/4 cycle, returns it to the system during the next 1/4 cycle etc. Ideally all stored energy would be returned, but this is not the practical case, a small amount is dissipated as heat in the dielectric. If we assume that energy is stored by stressing or moving dielectric atoms or molecules then we must assume there is friction, for energy is lost when heat is developed. The dissipation factor then is a function of shunt conductance where $G = 2\pi f \times PF$ mhos, where PF is the

dielectric dissipation factor. It equals the power factor for the high-quality dielectric commonly used, and is small for most large motors .

Capacitance: Another key indicator for insulation condition is capacitance. In increase in capacitance can sometimes indicate moisture intrusion, while thermally aged windings will show a decrease in capacitance over time, since the air-filled voids/delaminations have a lower dielectric constant, and therefore capacitance. Windings containing moisture will have a higher capacitance since the dielectric constant for water is ≈80, compared to 4 for epoxy-mica.

Conclusion: Based on the Characterization data a decision was made to also replace the stator for a second motor. Upon removal and disassembly at the OEM facility, the extent of stator system degradation was obvious and correlated to the characterization data analysis. The characterization data accurately assessed the condition of the motor and most likely prevented a motor from failing after the plant was back on-line. Characterization testing for predictive maintenance and troubleshooting can enhance effective/efficient resource allocation when used as part of a comprehensive condition monitoring program for all electrical equipment.